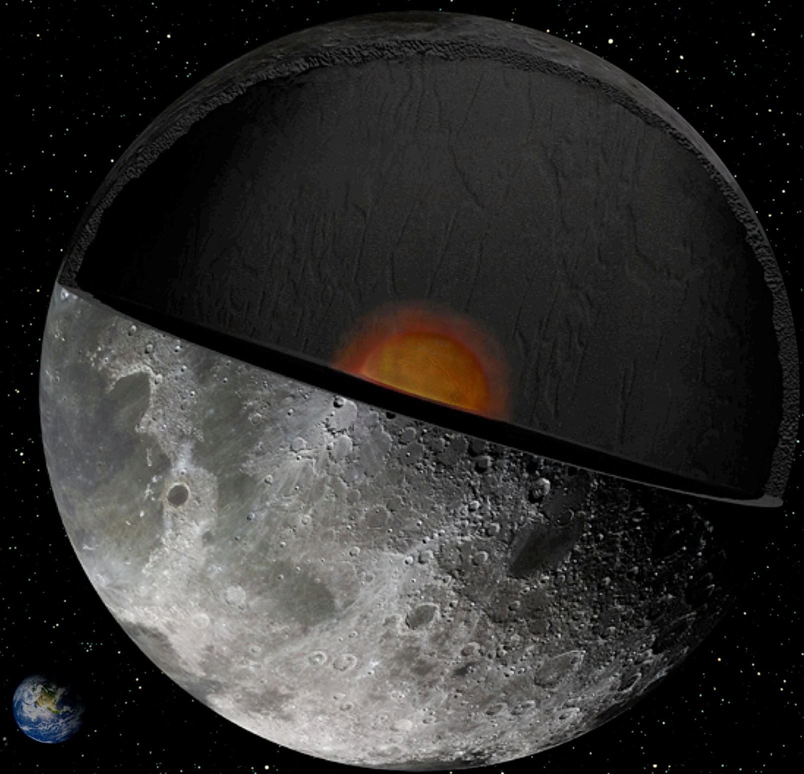
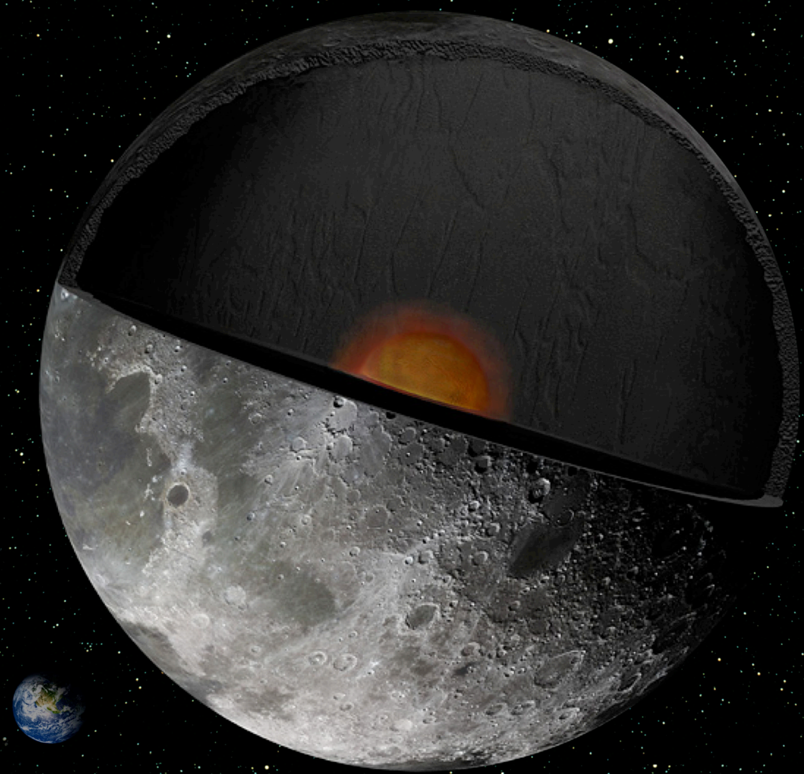


The Interior of the Moon

Maria T. Zuber

Lunar Science Forum
NASA Ames Research Center
Moffett Field, CA
July 22, 2009



There is no greater agony than bearing an untold story inside you.

-- Maya Angelou

Why study the Moon?

NASA/JPL/Galileo

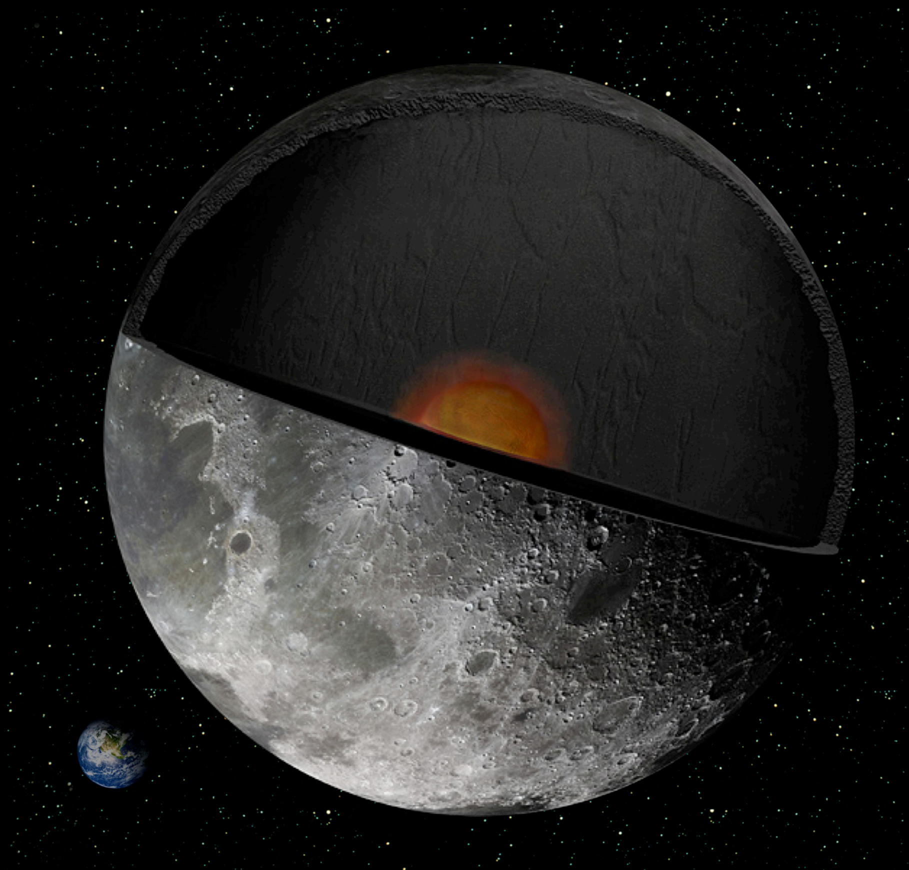
The Moon is the most accessible example of a rocky, differentiated planetary body that preserves a primordial surface, and is therefore *the key to understanding the formation and evolution of terrestrial planets.*

Thermal evolution:
heat sources and heat loss

External

Heating
- Impacts
- Orbit/ rotation

Cooling
- Radiation



Internal

Heating
- Differentiation
- Radioactive heating

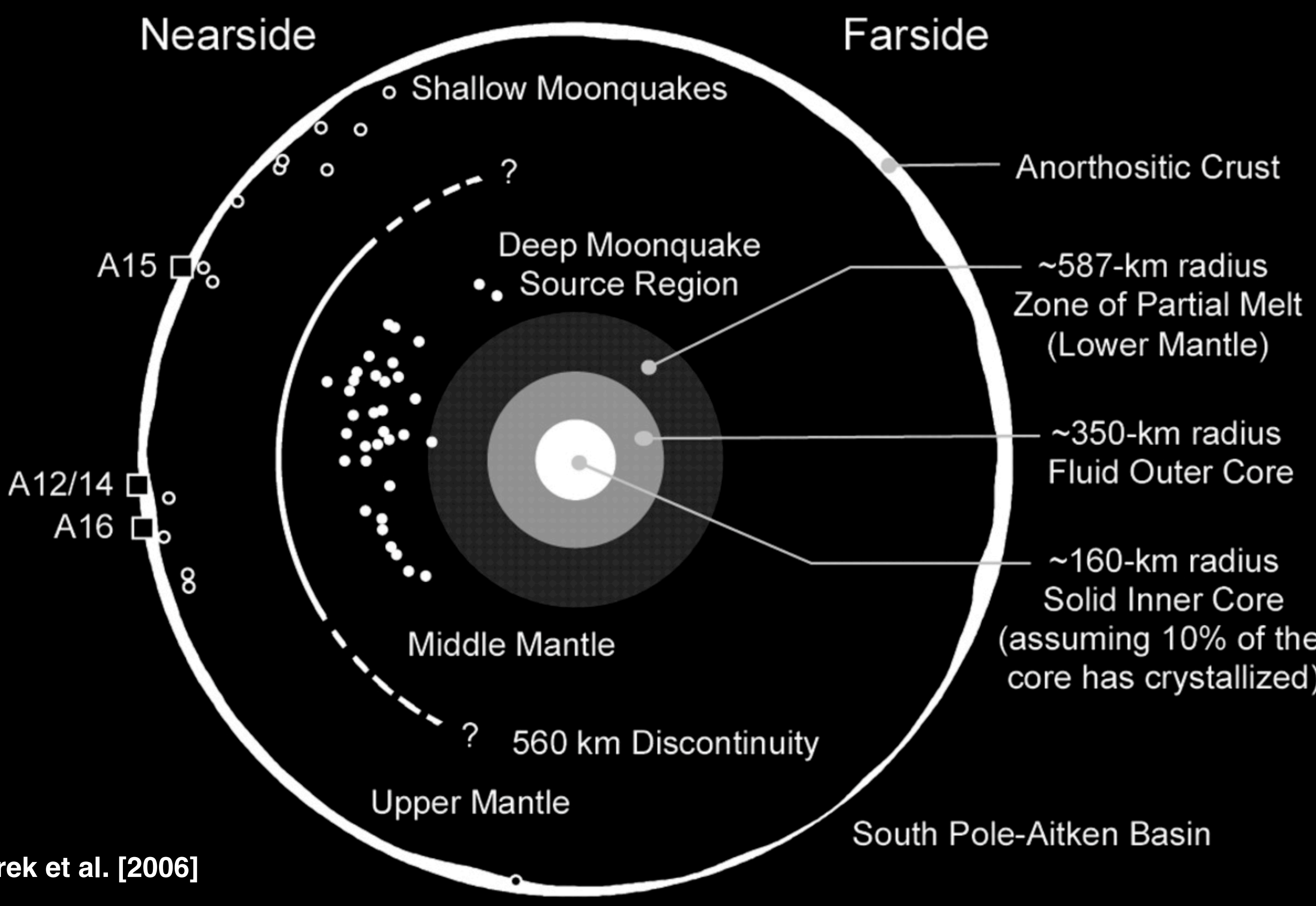
Cooling
- Conduction
- Convection
- Plumes

➔ *Reconstruct source/sink contributions throughout geologic time.*

Outstanding questions

- Why did the Moon apparently cool so early?
- Why does the Moon have an asymmetric structure (nearside/farside)?
- What is the thickness of the lunar crust?
- How much of crustal variability is due to variable melting vs. impact redistribution?
- What was the temporal evolution of magmatism and brecciation?
- How big are impact basins and how deep did they excavate and therrnally perturb the mantle?
- Did the mantle overturn subsequent to magma ocean solidification?
- How laterally heterogeneous is the lunar mantle?
- Does the Moon have a core?
- Does the Moon have a solid inner core?
- Did the Moon have a core dynamo?

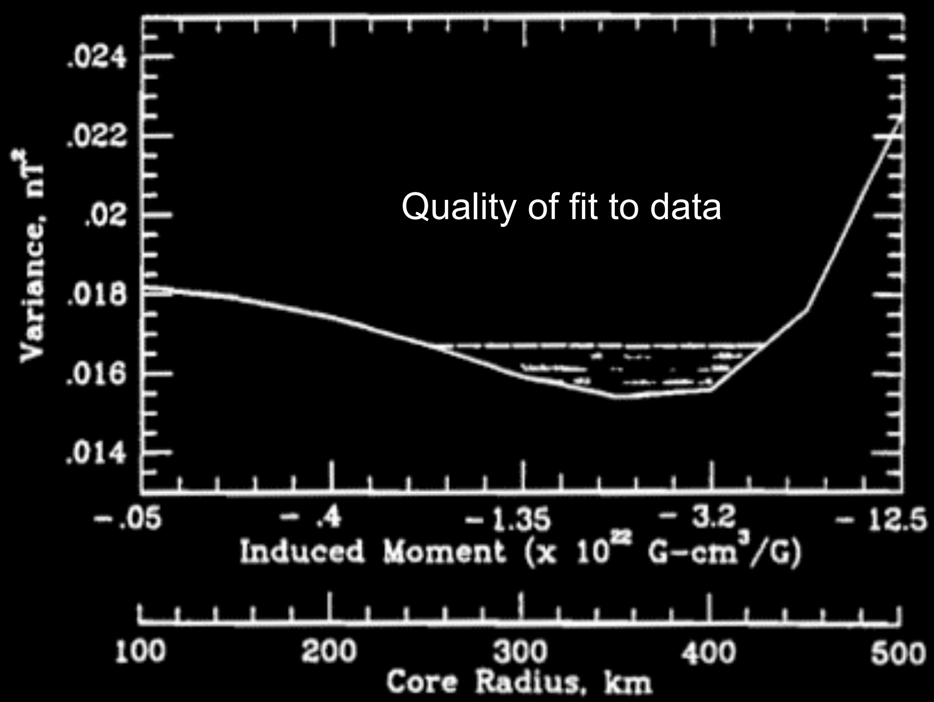
Notional view of lunar interior



Wieczorek et al. [2006]

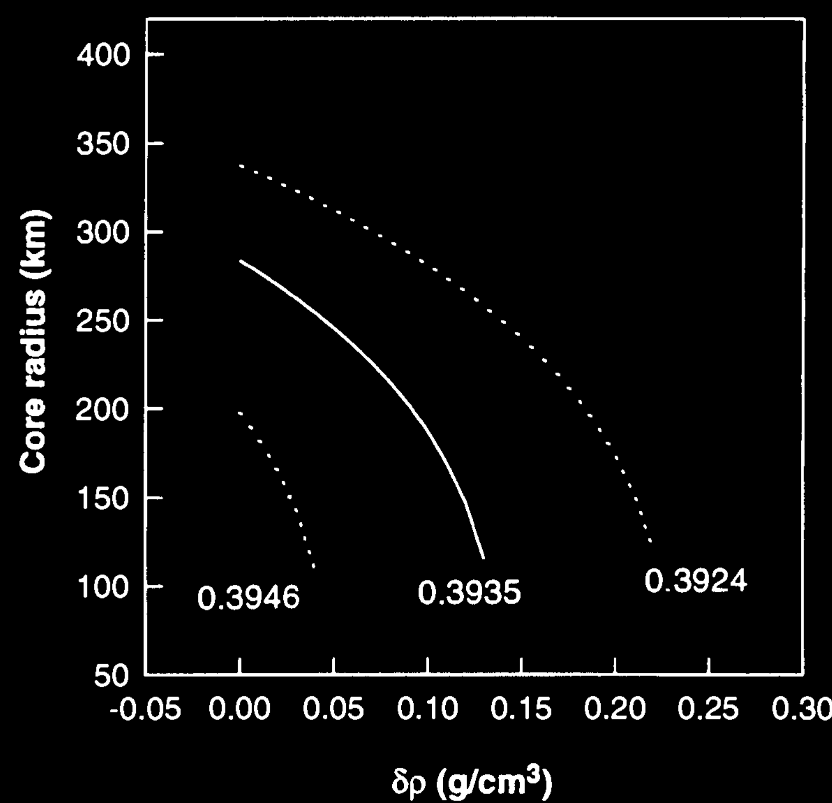
Deep interior: Evidence for core

Induced magnetic dipole moment



Hood *et al*. [1999]

Core radius vs. C/MR²



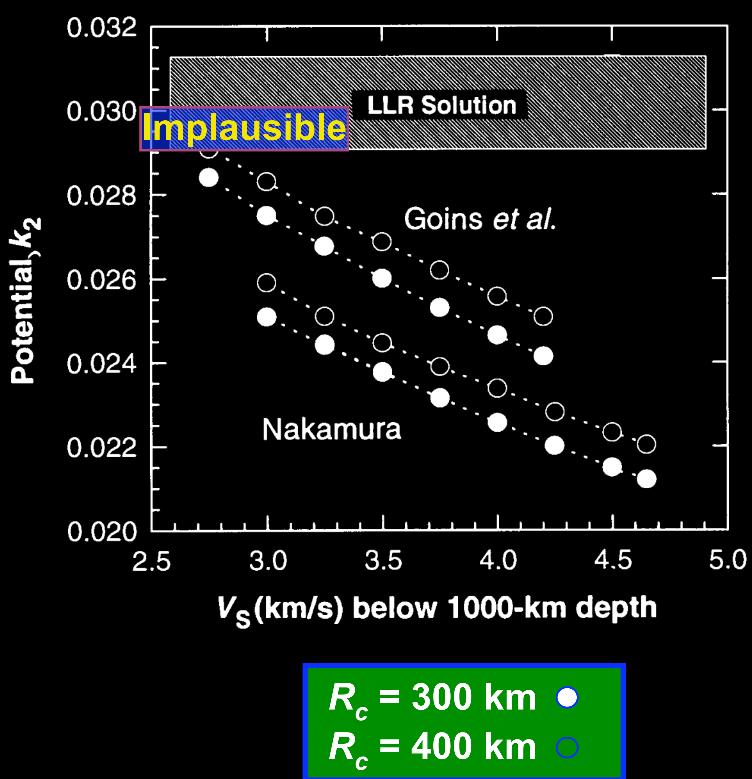
Dickey *et al.* [1994]

$C/MR^2 = 0.3940 \pm 0.0019$

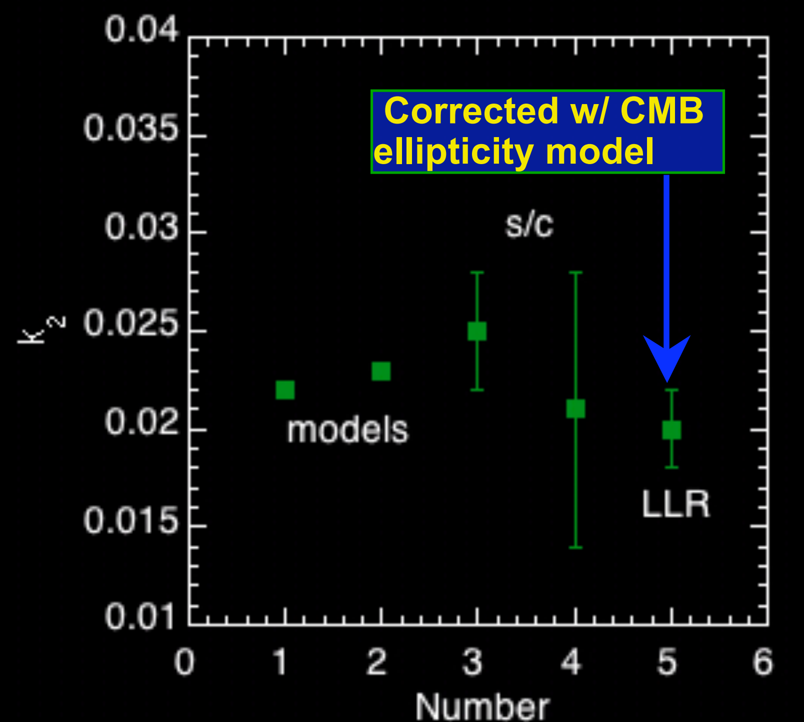
$220 < R_{Max\_core} < 350$ km

Deep interior: Evidence for core from k_2

Tidal Love Number



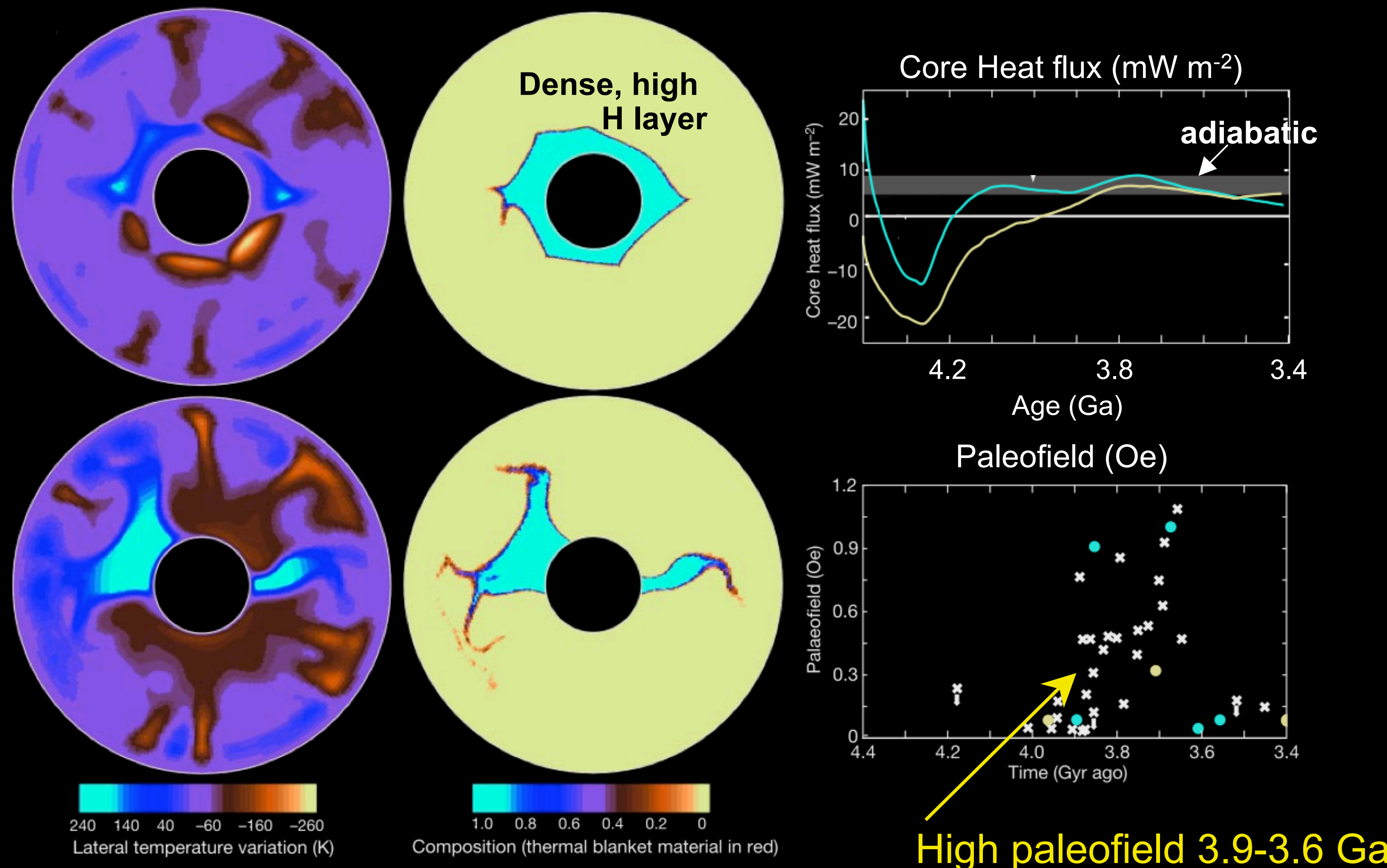
k_2 Model Values and Determinations



Dickey et al. [1994]

Konopliv et al. [1993]
Goosens and Matsumoto [2008]

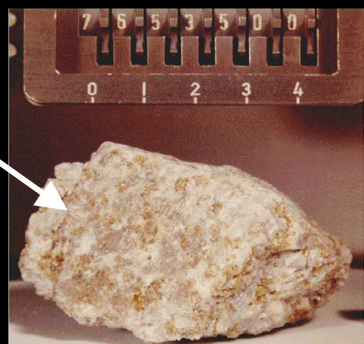
Was there a lunar core dynamo?

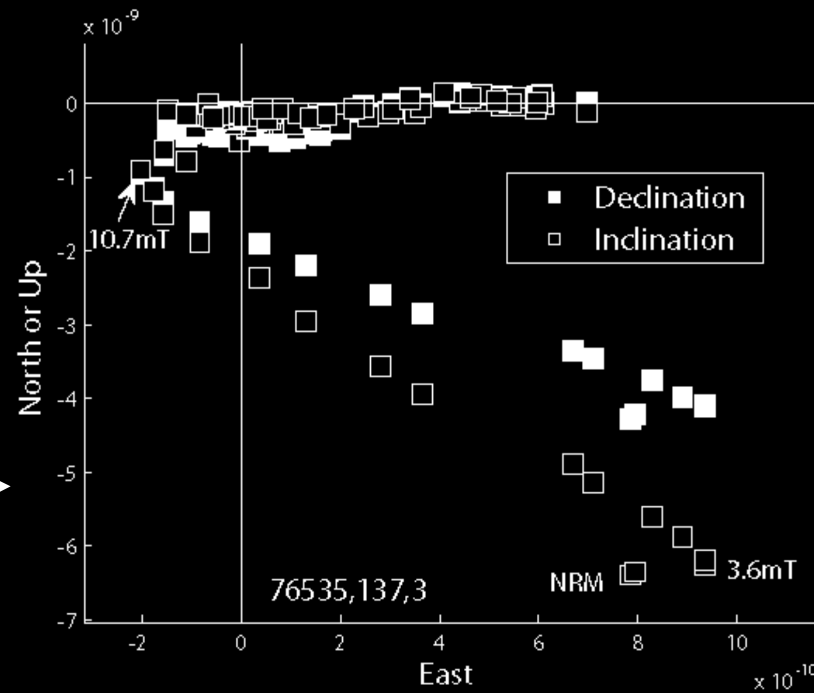


Stegman et al. [2003]

Early Lunar Magnetism

Remanent Magnetization in 76535 (4.2 Ga)

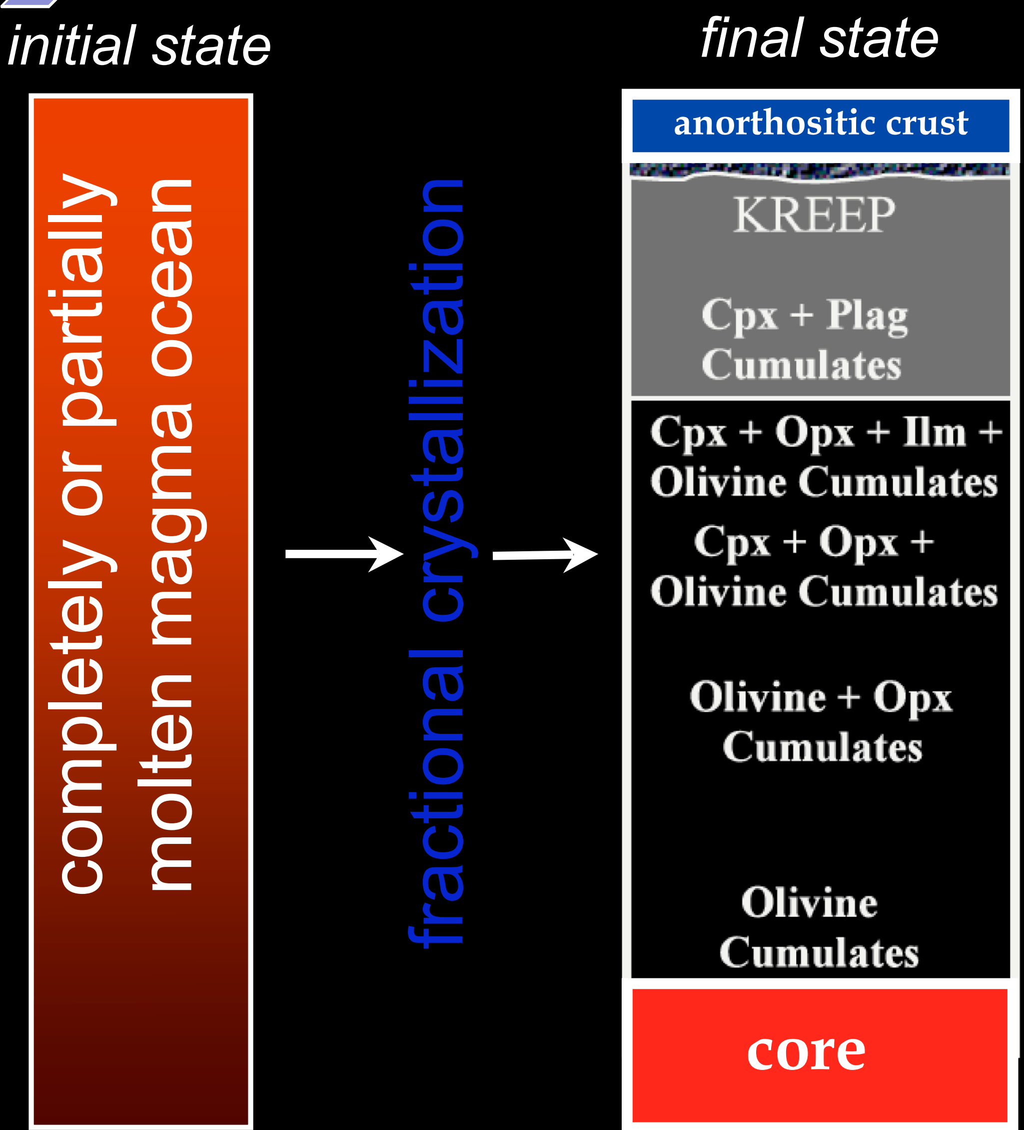




Garrick-Bethell et al. [2009]

- Magnetization in lunar rocks implies intense paleomagnetic fields (within an order of magnitude of Earth today).
- New analyses of ancient samples demonstrate that magnetic fields existed on the Moon as early as 4.2 Ga (before heavy bombardment).
- Ancient field cannot have come from Sun or Earth. May have come from an early core dynamo.

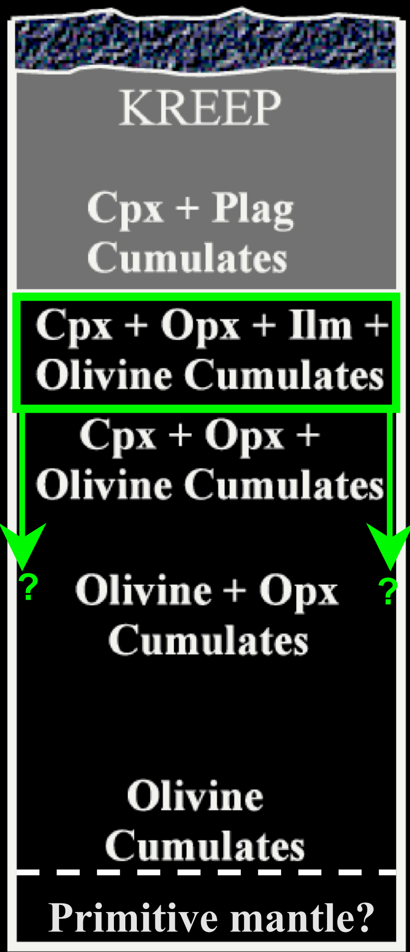
Magma ocean crystallization: Nominal view



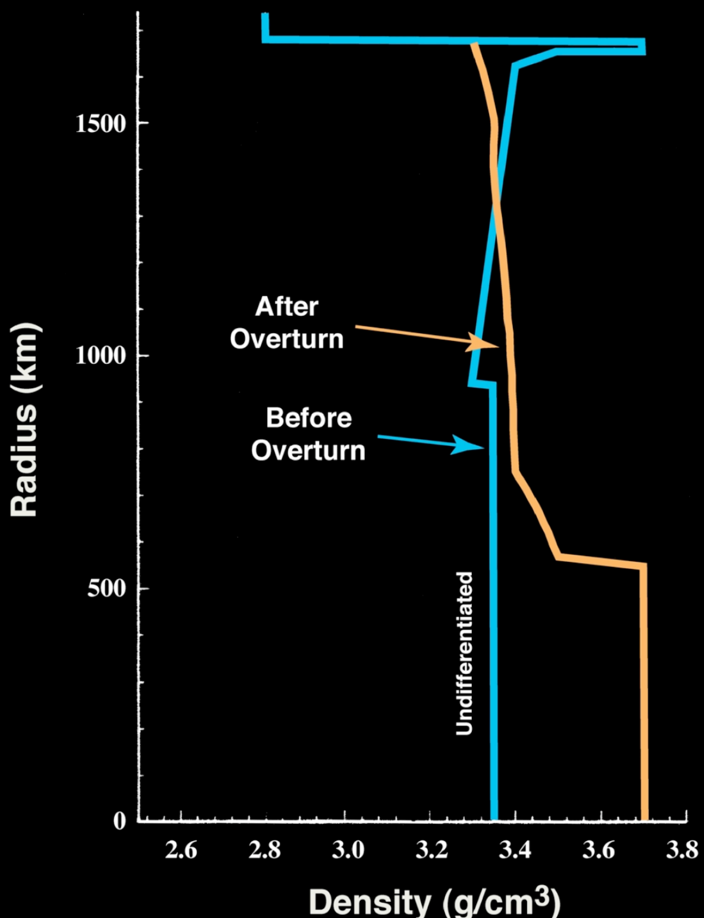
- First minerals to crystallize are Mg-rich olivines, which sink.
- As crystallization proceeds, cumulates become more iron rich, and dense.
- After ~75% crystallization, anorthite (plagioclase) begins to crystallize, and floats.
- Last liquids to crystallize are enriched in heat producing and incompatible elements (*i.e.,* KREEP), concentrated in western nearside.

Shearer et al. [2006]

Did the mantle overturn?

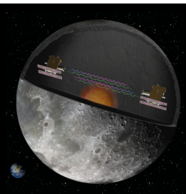


Shearer *et al.* [2006]

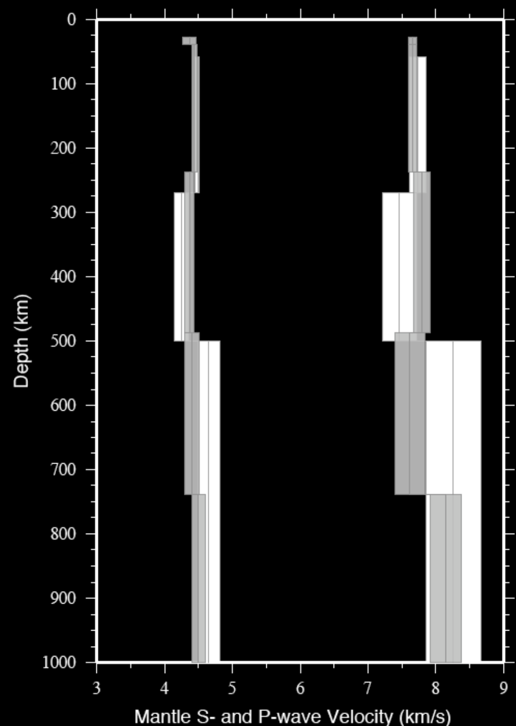


Hess & Parmentier [1995]

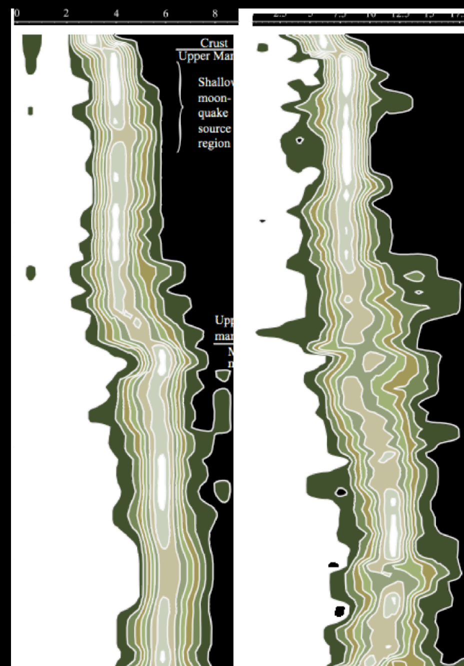
- After magma-ocean crystallization, mantle is gravitationally unstable, with dense Fe/Ti-rich cumulates overlying Mg-rich cumulates.
- Mantle could have overturned bringing deep Mg-rich cumulates to upper mantle and sending Ti- and Fe-rich cumulates to the deep interior.



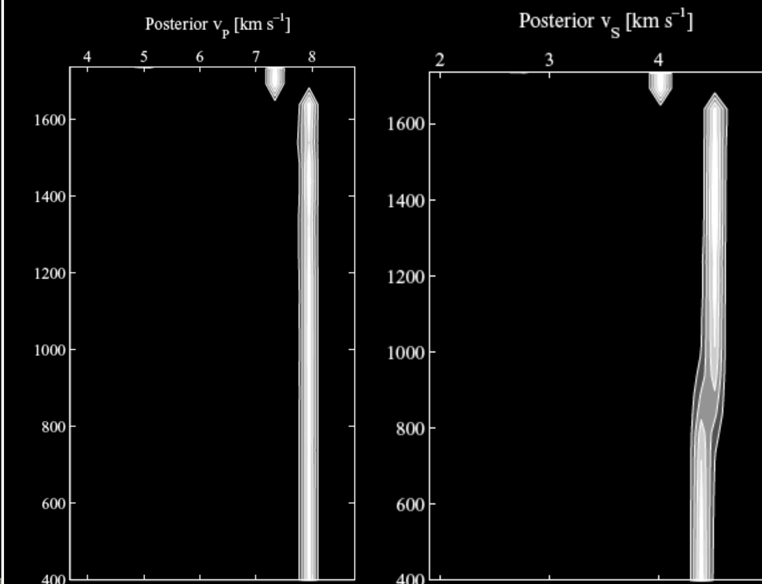
Is there a seismic discontinuity in the mantle?



Nakamura et al. [1982],
Lognonné et al. [2003]
Maybe: ~500 km



Khan and Mosegaard [2002]
Yes: 550 km depth

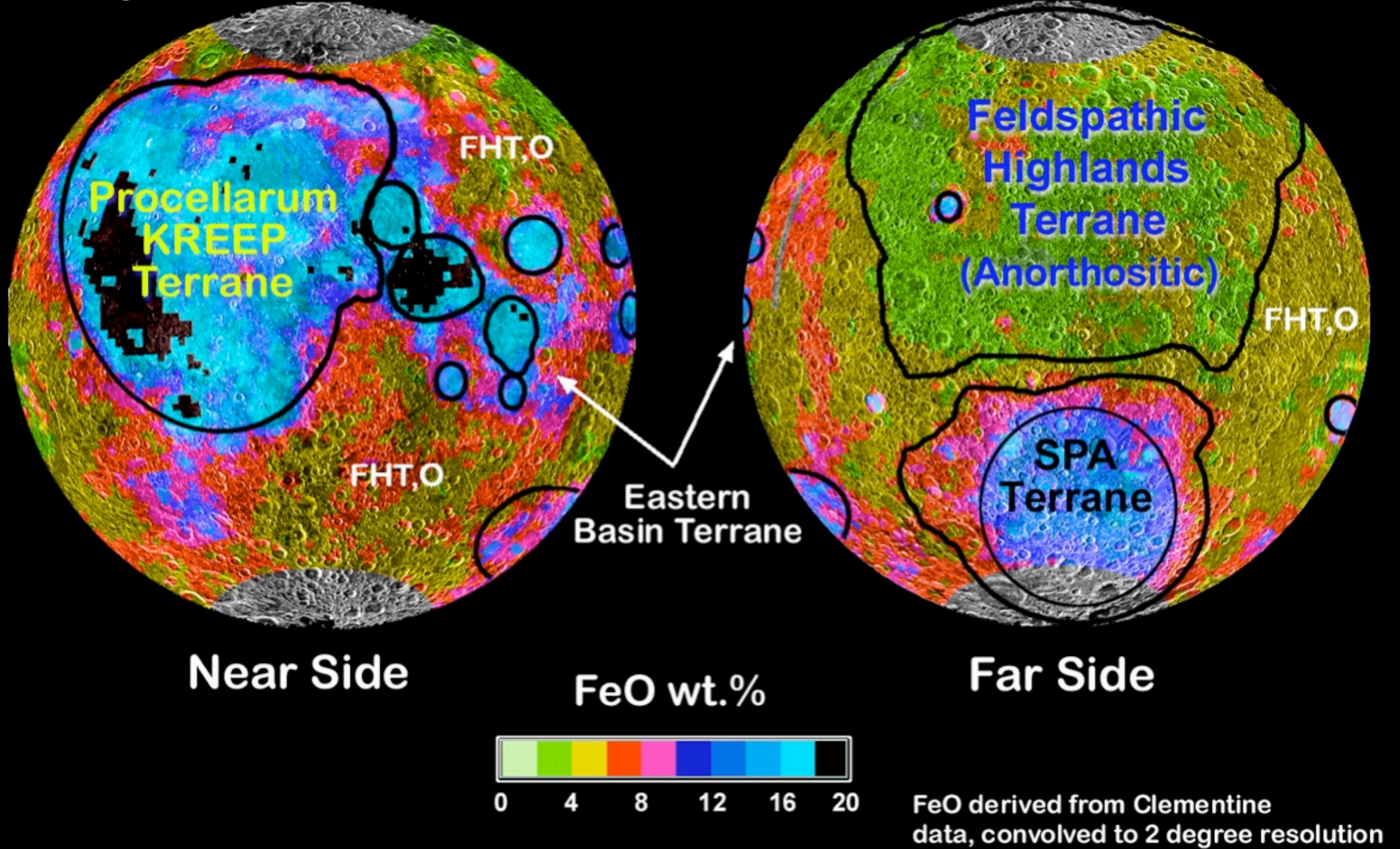


Khan et al. [2007)]
NO? or 850 km depth?

Each study used different seismic events, seismic arrival times and analysis techniques... *so don't know the answer, <u>but important for magma ocean depth</u>.*

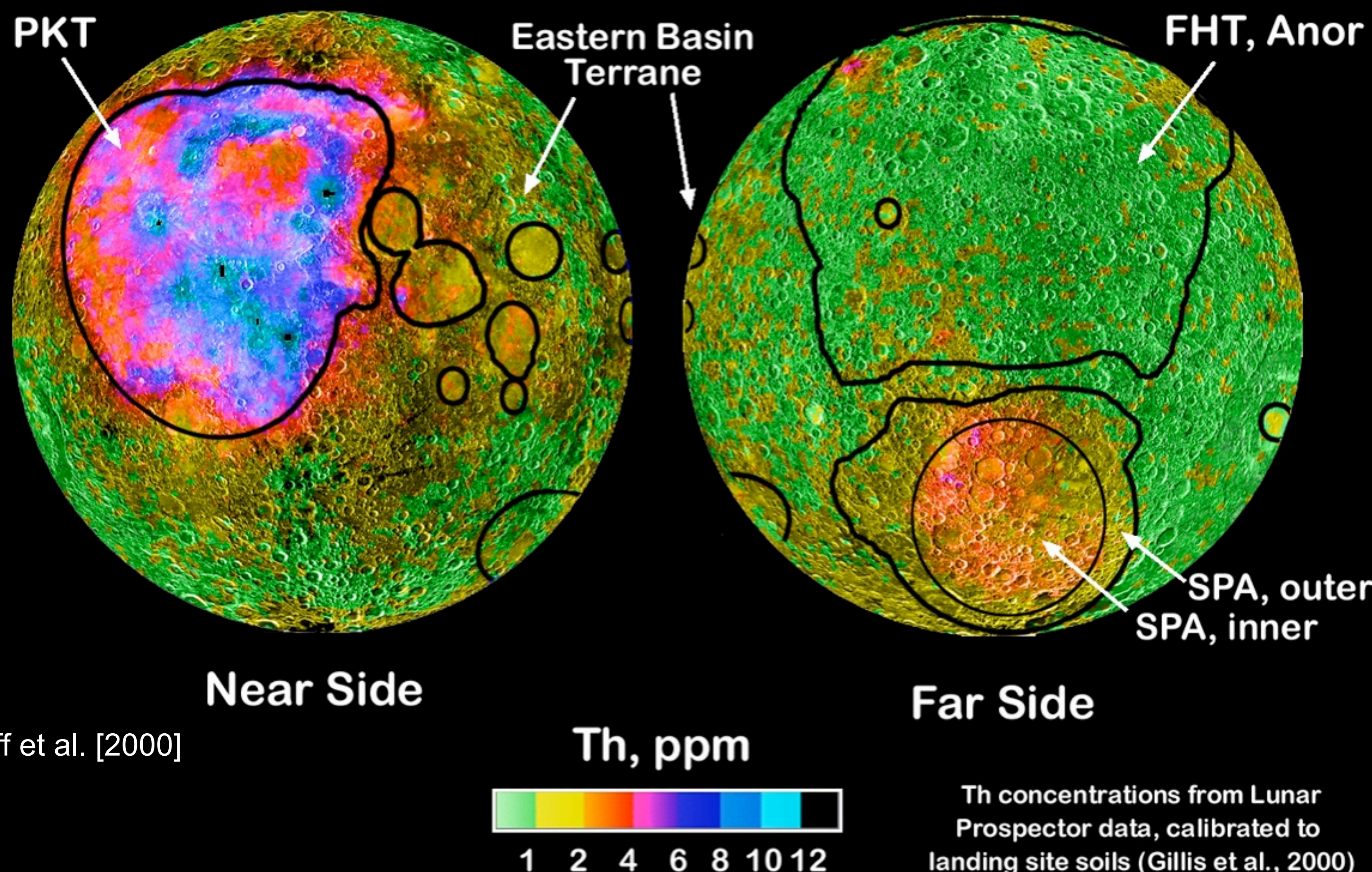
Evidence for lunar magma ocean

A large portion of lunar crust is composed of anorthositic materials.



Jolliff et al. [2000]

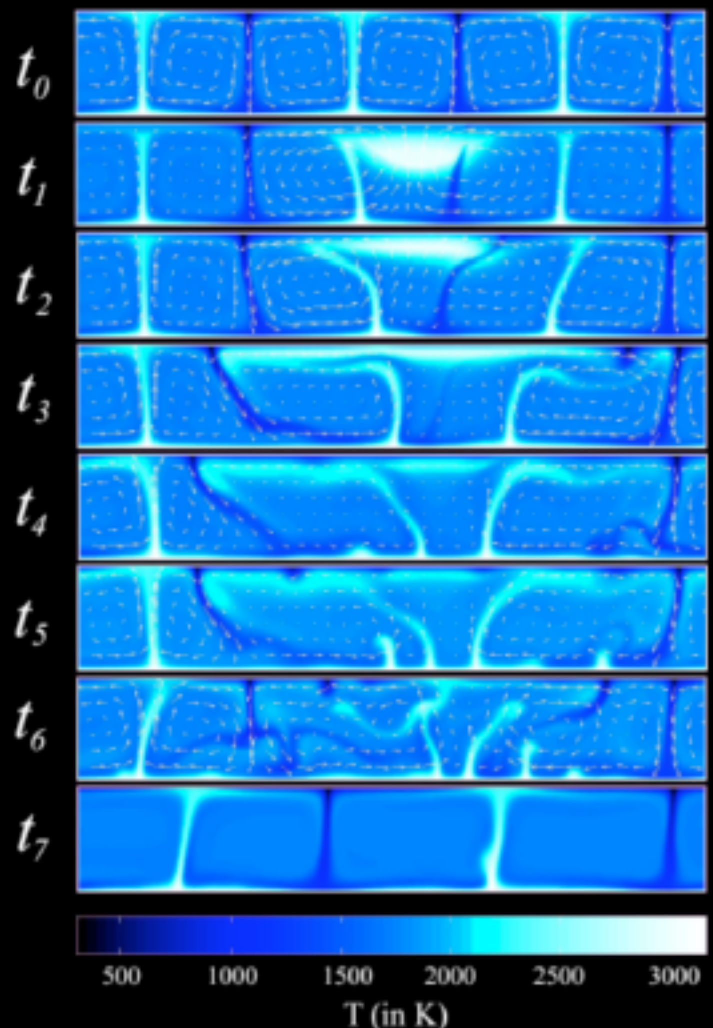
Evidence for enhanced near side melting



Jolliff et al. [2000]

Lunar Prospector γ-ray spectroscopy shows that Th, and by inference KREEP, is highly concentrated only in a near side crustal province: the <u>Procellarum KREEP Terrane</u> (PKT).

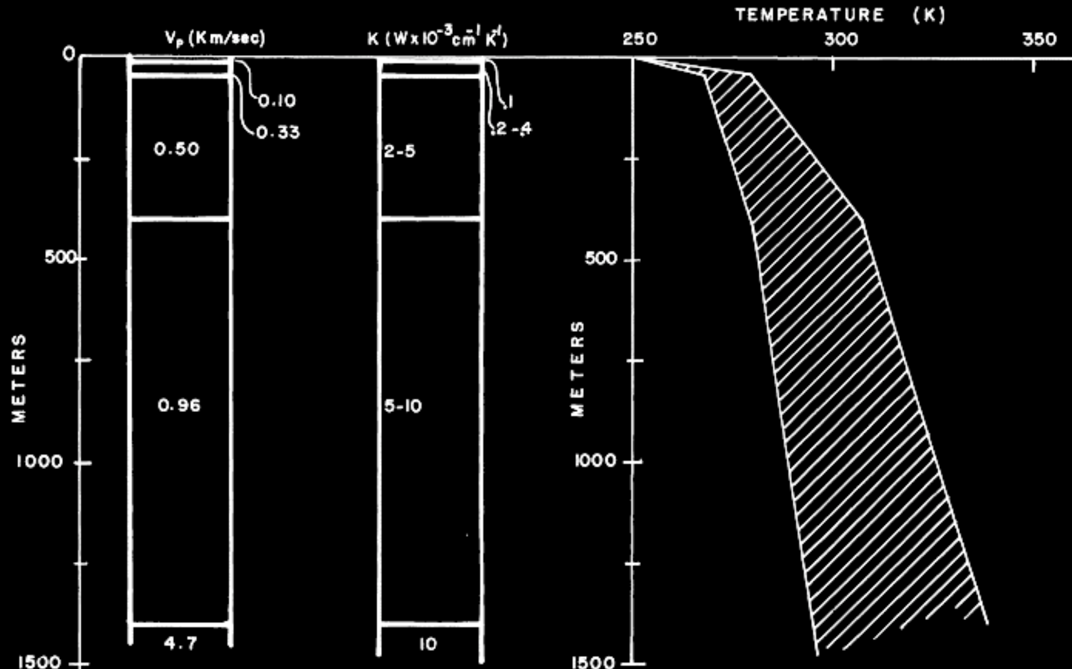
How did large impacts thermally perturb the mantle?



Watters, Zuber & Hager [2009]

- Major impacts heat crust & mantle and transmit heat into core.
- Plume formation favored beneath thermal anomaly.
- Chaotic convective period ensues.
- Enhanced surface volcanism throughout

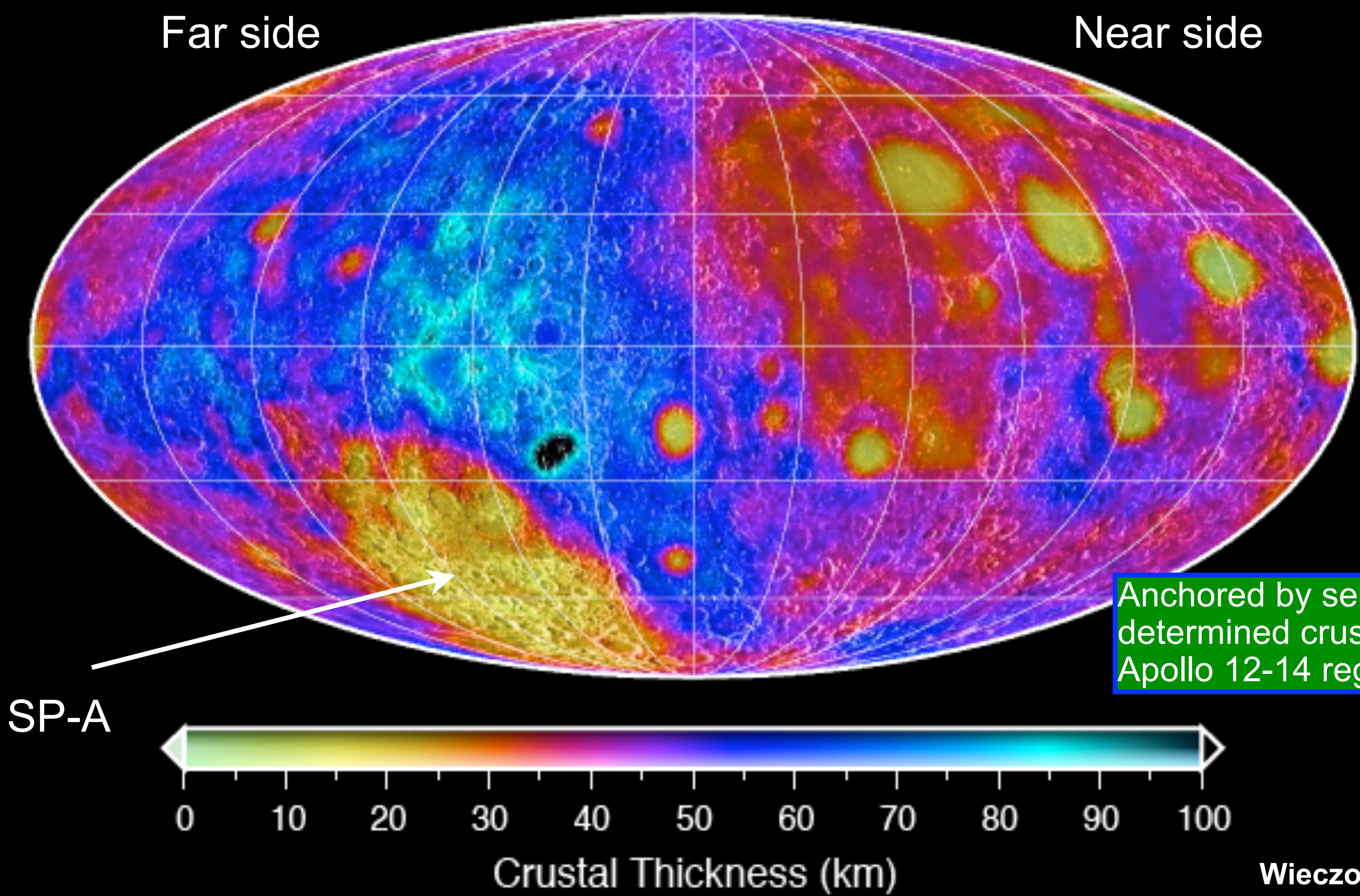
Current boundary condition – heat flow



Langseth et al. [1976]

- Apollo heat flow experiments revealed:
  - regolith is extremely insulating.
  - surface thermal environment is readily disturbed by compaction and/or albedo changes.
  - lunar heat flow is spatially variable, necessitating distributed measurements to constrain local variations and distinguish among hypotheses.

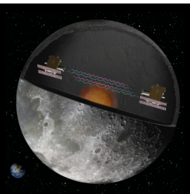
Crustal thickness modeling



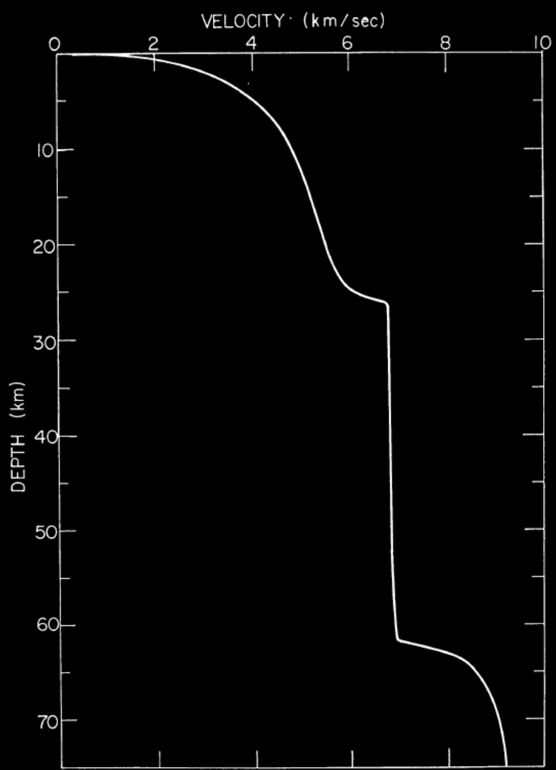
Anchored by seismically-determined crustal thickness in Apollo 12-14 region

Wieczorek et al. [2006]

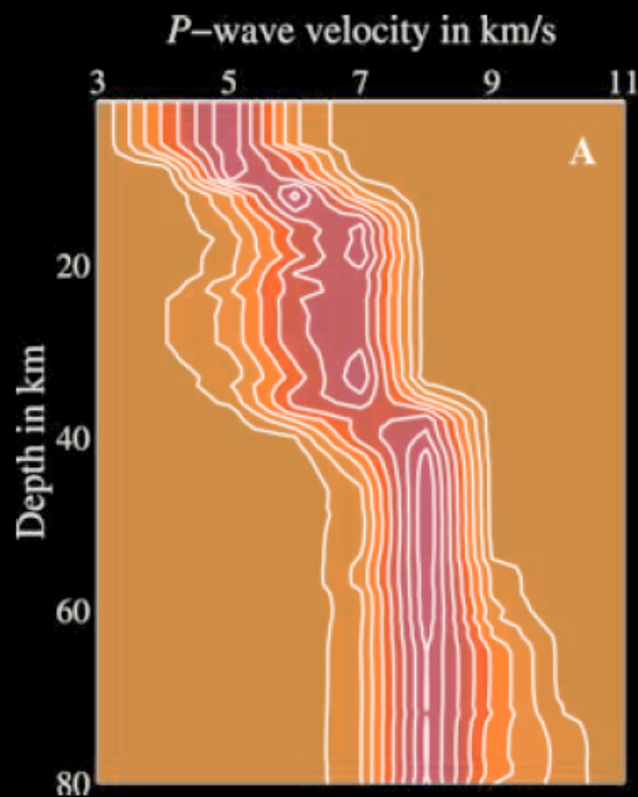
Gravity anomalies can be modeled in terms of crustal thickness variations, showing that large impact events excavated large quantities of crustal materials.



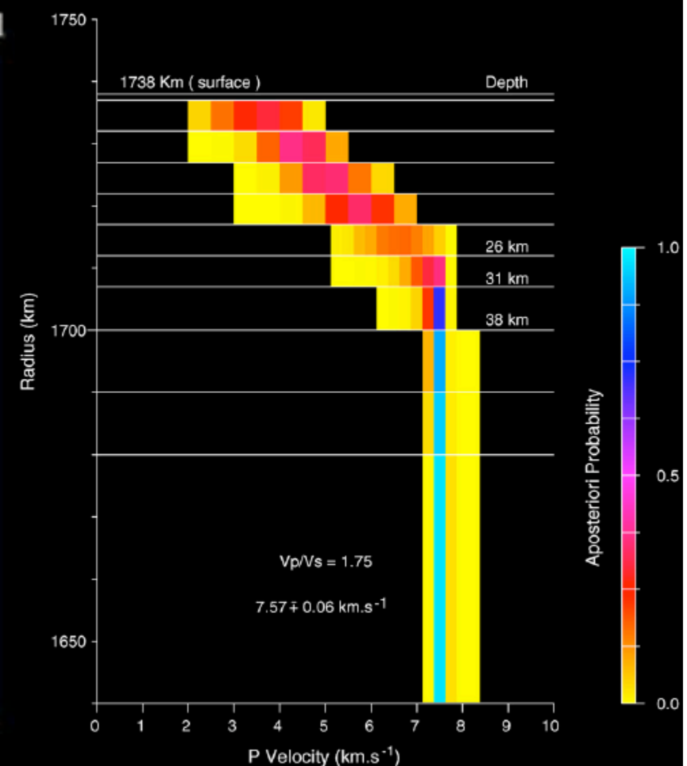
Constraints on crustal thickness from seismology



Toksöz et al. [1972]
~60 km



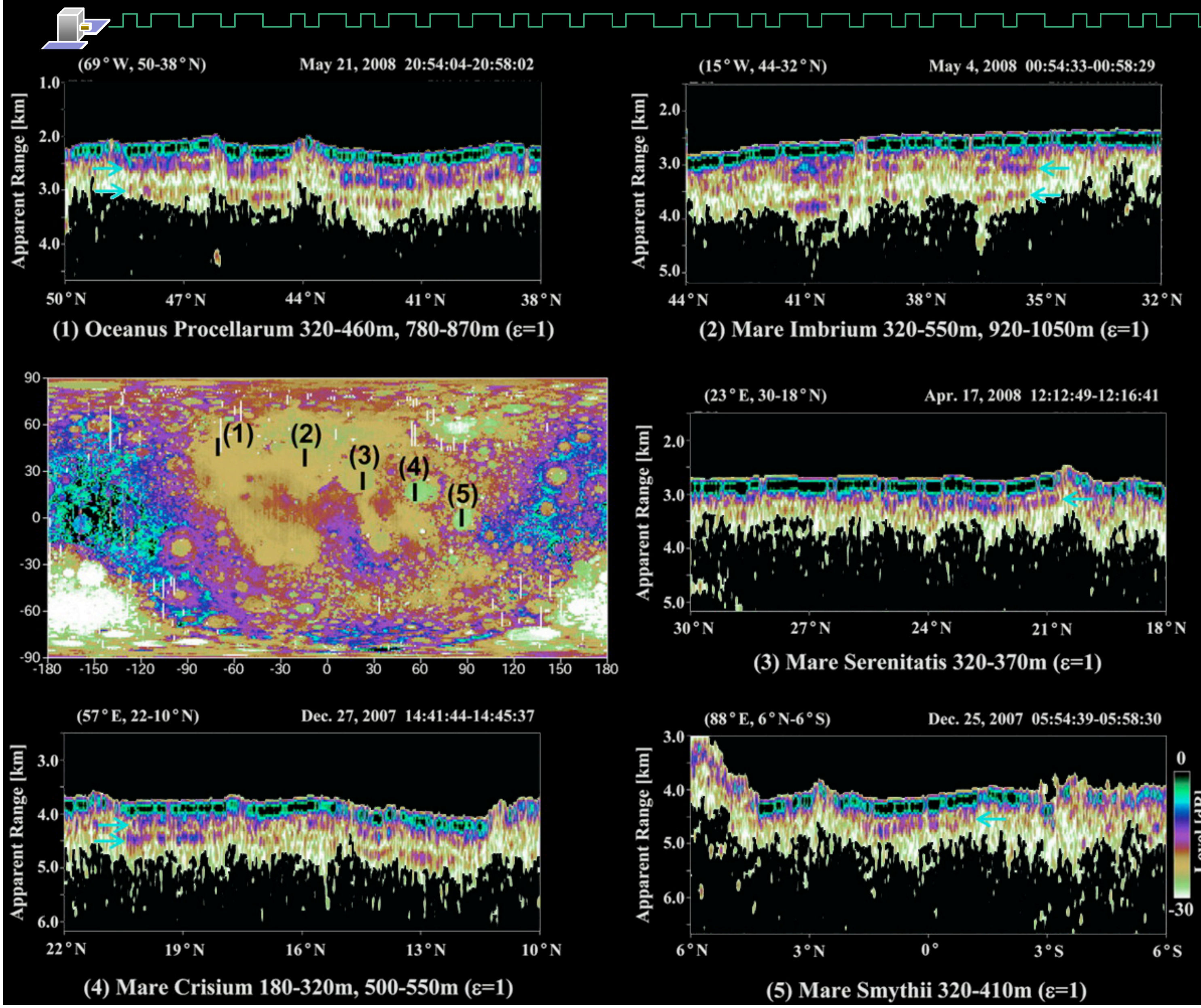
Khan and Mosegaard [2002]
38±3 km



Lognonné et al. [2003]
30±3 km

Each study used different seismic events, seismic arrival times and analysis techniques...

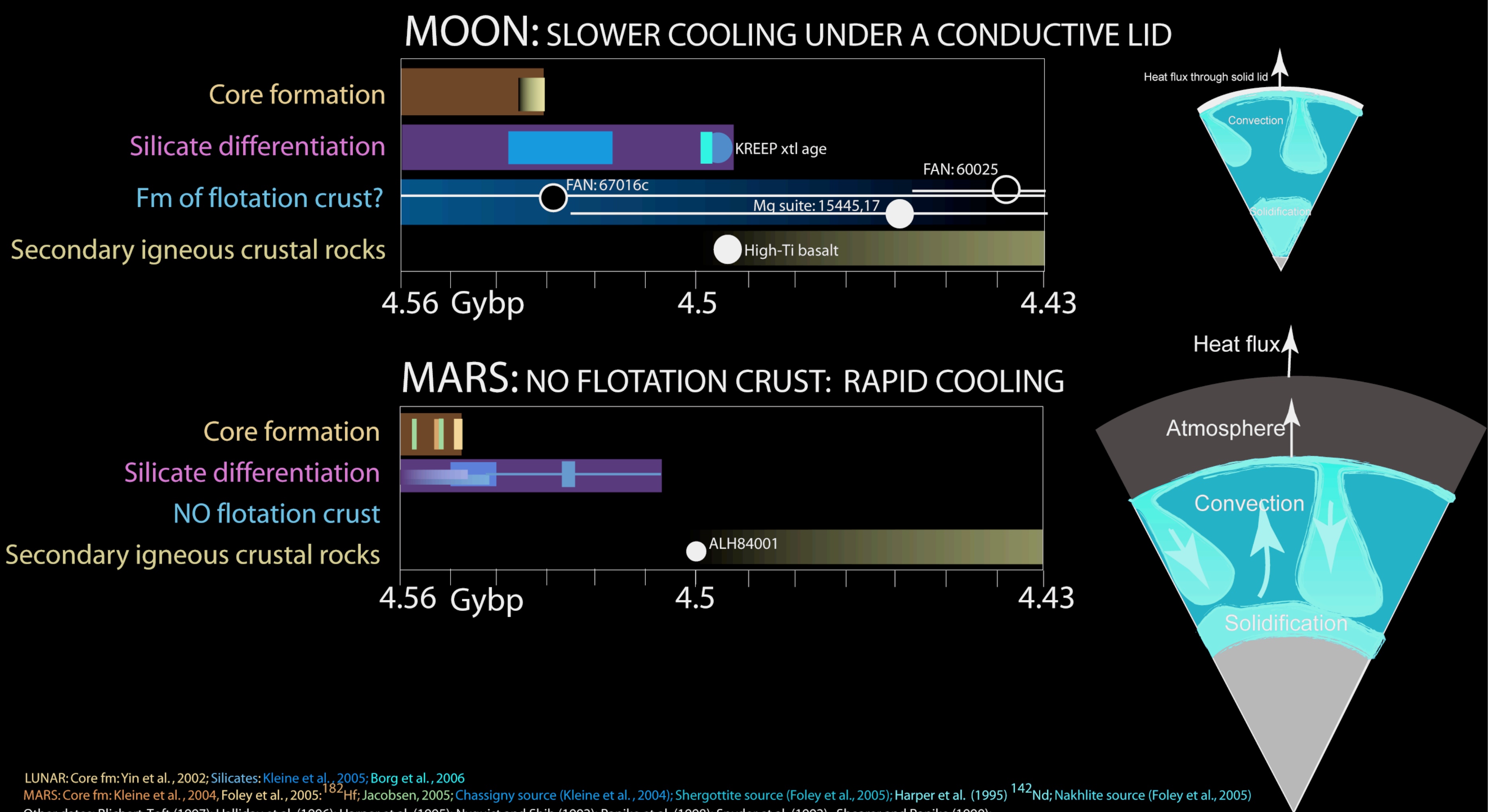
What is the distribution of regolith?



Elucidates interplay between bombardment & volcanism.

Ono et al. [2009]

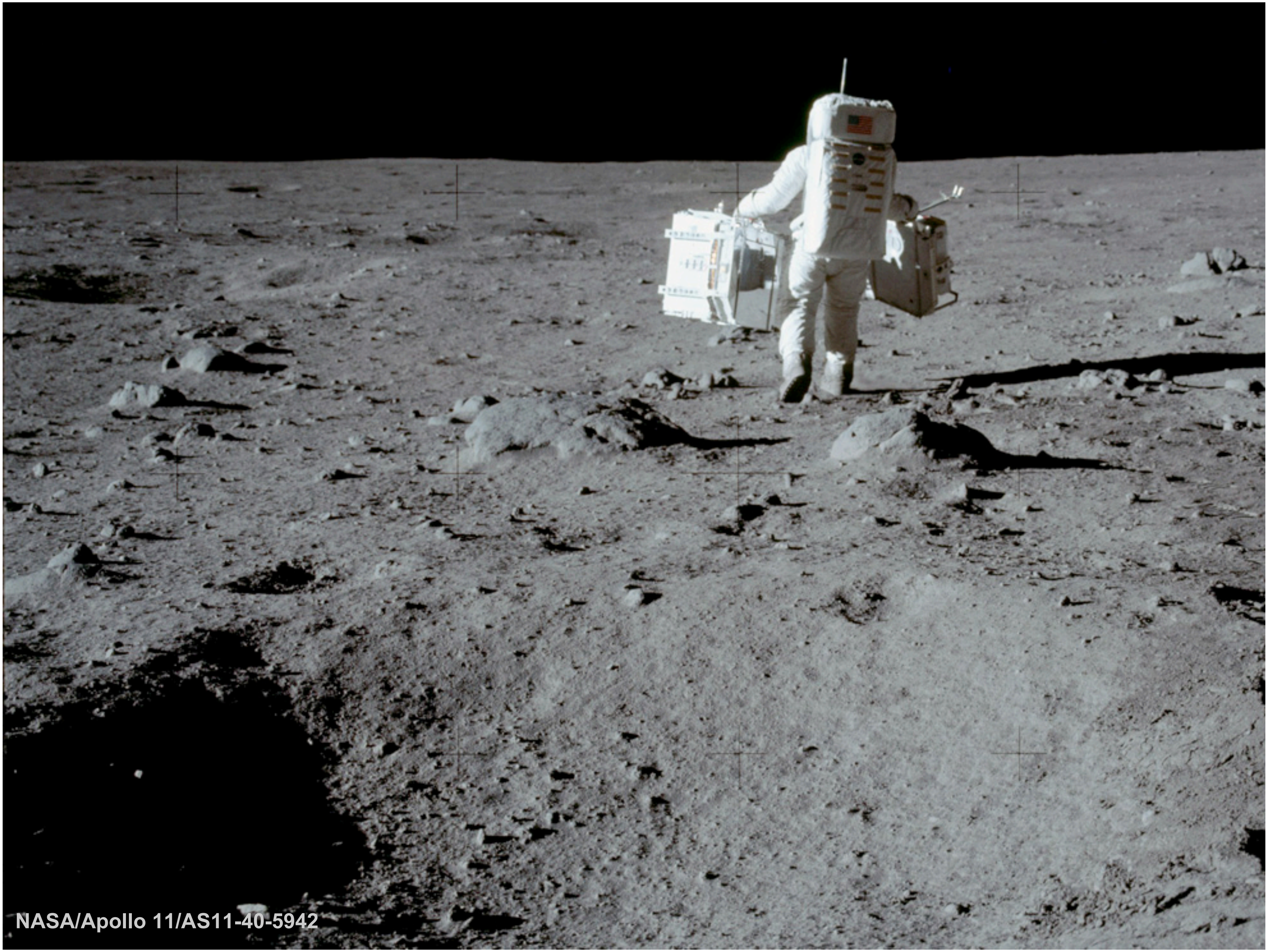
Comparative magma oceanography



LUNAR: Core fm: Yin et al., 2002; Silicates: Kleine et al., 2005; Borg et al., 2006
MARS: Core fm: Kleine et al., 2004, Foley et al., 2005: ^{182}Hf; Jacobsen, 2005; Chassigny source (Kleine et al., 2004); Shergottite source (Foley et al., 2005); Harper et al. (1995) ^{142}Nd; Nakhlite source (Foley et al., 2005)
Other dates: Blichert-Toft (1997); Halliday et al. (1996); Harper et al. (1995); Nyquist and Shih (1992); Papike et al. (1998); Snyder et al. (1992), Shearer and Papike (1999);

Elkins-Tanton [2008]

GRAIL


NASA/Apollo 11/AS11-40-5942